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(54) Electrically-variable inductor.

(57) An inductive device includes a principal magnetic core (11) having a principal winding (10) coupled therewith so that the reluctance of the principal core influences the inductance of the principal winding. A control winding (12) is coupled to a control magnetic core (13) so that the current in the control winding influences the magnetic flux in the control core. The control core intersects the principal core so that magnetic flux produced in the control core interferes with the principal core. Selective control of current in the control winding influences the magnetic flux in the control core, which in turn interferes with the principal core so as to influence the reluctance thereof and thereby vary the inductance of the principal winding. Additional control windings may be coupled to respective additional control cores (13a, 13b, 13c) which intersect the principal core, so that selective control of the currents in the various control windings enables selective control of the degree of interference with the principal core, and hence the reluctance thereof. The dim nsions of resp ctive reluctance control regions where the control cores intersect the principal core may be s l cted such that the degrees of influence of the individual control cores are in a binary sequence.

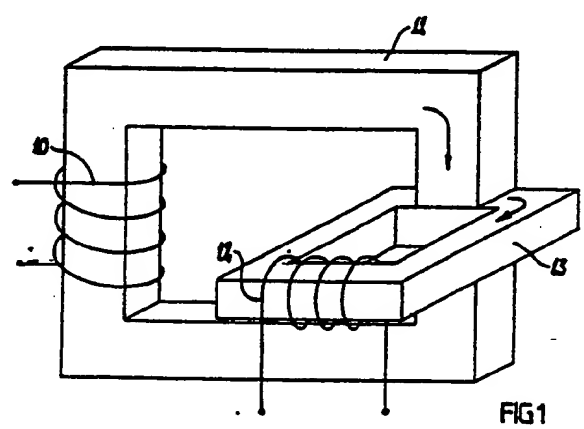

FIG1

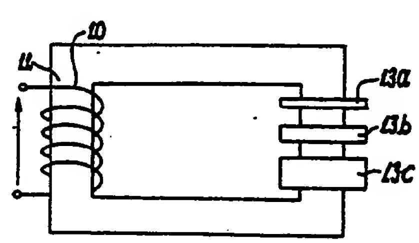

FIG 3

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ELECTRICALLY-VARIABLE INDUCTOR

This invention relates to variable inductive devices such as variable inductances and transformers.

In the past, the selective control of inductance has been effected by mechanically altering the physical characteristics of either the electrical circuit or the magnetic circuit associated with the inductor. These techniques can be costly, mechanically unreliable, and inadeuqate for the purpose of varying inductance in response to electrical control signals. In the cases of magnetic amplifiers and voltage regulating transformers, the steady state interaction which can occur between the control circuits and the power circuits as a result of magnetic coupling constitutes a distinct disadvantage for many applications.

It is an object of the present invention to provide an electrically-variable inductive device.

In a preferred embodiment of the invention an electrically-variable inductive device is provided having means for controlling values of inductance within an electrical circuit in response to application of one or more control signals to one or more respective control circuits, without, or with only negligible, magnetic coupling between any of the circuits.

The invention is based on the idea of electrically controlling the reluctance of a magnetic circuit, and of thereby controlling the inductance of one or more electrical inductors associated with the magnetic circuit.

In particular, the invention is based on the idea of controlling values of inductance in an electrical circuit by selectively switching current levels, which may be quite low, in one or more magnetically associated control circuits, preferably without the incumbent disadvantage of magnetic coupling between any of the individual circuits. The advantages of such an approach relative to the aforementioned prior art include the total absence of moving parts which results in ruggedness and economy of construction, the ability to control large amounts of power using low-level direct current signals, and the virtual absence of magnetic coupling between any of the individual circuits of the device.

According to the invention there is provided an inductive device including a principal winding, and a principal magnetic circuit having the principal winding operatively coupled therewith so that the reluctance of th principal magnetic circuit influences the inductance of the principal winding, characterised by a control winding; and a control magnetic circuit having th control winding operatively coupled therewith whereby the current in th control winding influences the magnetic flux in the control magnetic circuit, the control magnetic circuit being arranged in association with the principal magnetic circuit so that a magnetic flux in the control magnetic circuit at least partially interferes with the principal magnetic circuit, whereby selective control of current in the control winding influences the magnetic flux in the control magnetic circuit which in turn interferes with the principal magnetic circuit so as to thereby influence th reluctance thereof and so vary the inductance of the principal winding.

Preferably the control magnetic circuit is arranged substantially in a single control plane, the control plane being arranged substantially at right angles to at least the region of the principal magnetic circuit subject to the interference by magnetic flux in the control magnetic circuit. Also preferably the principal magnetic circuit is arranged substantially in a single principal plane at right angles to the control plane, whereby magnetic coupling between the control magnetic circuit and principal magnetic circuit is minimised.

If desired, one or more additional control windings may be provided, the or each additional control winding being operatively coupled with a respective additional magnetic control circuit arranged relative to the principal magnetic circuit so as to interfere therewith, this arrangement enabling selective control of the currents in the control winding and in the or each additional control winding so as to enable selective control of the degree of interference with the principal magnetic circuit, and hence the reluctance thereof.

Also if desired, there may be provided at least one additional principal winding operatively coupled with the principal magnetic circuit so as to enable inductive coupling between the principal winding and the or each additional principal winding, the arrangement being such that the selective control of the current in the control winding enables selective variation of the inductance of and coupling between the principal winding and the or each additional principal winding.

In the preferred construction of a device according to the invention the principal magnetic circuit comprises a principal magnetic core, and the control magnetic circuit comprises a control magnetic core. The control magnetic core intersects the principal magnetic core so as to enable selective interference with the reluctance of th principal magnetic core by selective control of current in the control winding. Preferably the control winding is arranged to be completely de-energised or to be

energised to an extent that the associated control magnetic core is magnetically saturated. The control magnetic core is preferably made of a high permeability ferromagnetic material.

In one particular possible arrangement of a device according to the invention, the principal magnetic core is divided into two loops which are intersected symmetrically by a single control magnetic core, the single control core having coupled therewith two symmetrical control windings connected in parallel, whereby any magnetic flux set up by the principal core in the intersecting control core carrying the control windings is self-cancelling and vice versa, whereby any magnetic cross-coupling between the principal and control magnetic circuits is substantially reduced.

In any of the embodiments using the preferred magnetic cores, the principal magnetic core may have a portion thereof with defines a series portion of the principal magnetic circuit, this core portion being intersected by a plurality of control magnetic cores each having associated therewith a respective control winding, whereby selective control of the number of control windings energised enables selective control of the reluctance of the series portion of the principal magnetic circuit. In this arrangement, each of the plurality of control magnetic cores may have a respective different thickness at least at the intersection thereof with the core portion, so that each control magnetic core can influence the reluctance of the principal magnetic circuit to a different predetermined extent.

The principal magnetic core in a further possible embodiment may be divided into parallel core portions providing parallel paths for magnetic flux in the principal magnetic core, each of the parallel core portions being intersected by a respective control magnetic core, each control magnetic core having an associated respective control winding, whereby selective control of the current in each control winding enables selective control of the magnetic reluctance in the respective associated parallel core portion of the principal magnetic core.

The dimensions of each respective reluctance control region where each control magnetic core intersects the principal magnetic core may be chosen and arranged so as to enable selective stepping of the principal winding inductance. In particular, the individual degrees of influence of the control magnetic cores may be in a binary sequence so that not only each individual control magnetic core influences the reluctance of the principal magnetic circuit to a respectively different extent, but also different permutations and combinations of control magnetic cores, when the associated control windings ar energised, will also influence the reluctance of the principal magnetic circuit to respectively differing extents. The device may be associated with, or have included therein, switching means responsive to a binary coded input signal, the switching means being operative to switch circuit to respective different combinations of the control windings in response to the binary coded signal so as to thereby enable control of the inductance of the principal winding in a stepped fashion.

In one particular preferred use of the invention, the principal magnetic circuit may have associated therewith a secondary winding so as to enable magnetic coupling between the principal and secondary windings, control of the current in the control winding thereby enabling selective control of the magnetic coupling between the principal and secondary windings. In a particular configurati n, the principal magnetic circuit may include a control arm and principal arms symmetrically arranged relative to the control arm, the control arm having associated therewith the control magnetic circuit, the principal winding being operatively associated with one of the principal arms, the secondary winding being arranged in two stages in series, each stage being operatively associated with a respective one of the two principal arms.

A power factor compensation arrangement may utilise a variable inductive device according to the present invention arranged in parallel with capacitive means, enabling compensation against fixed or variable reactive imbalances in an associated power circuit.

Embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which

Figure 1 is a schematic perspective view of a basic arrangement of an inductive device according to the invention;

Figure 2 is a schematic perspective view of a further embodiment of an inductive device according to the invention;

Figure 3 is a schematic side view of a preferred embodiment with three control magnetic circuits disposed in a series arrangement in the principal magnetic circuit;

Figure 4 is a schematic side view of a preferred embodiment having three control magnetic circuits disposed in a parallel arrangement with the principal magnetic circuit;

Figure 5 is a schematic side view of a voltage regulating transformer according to an embodiment of the invention; and

Figure 6 is a schematic circuit diagram of a simple power factor compensating circuit utilising the present invention.

Referring to the accompanying drawings, Figure 1 illustrates a basic exemplary embodiment of a variable inductive device according to th invention. A principal winding 10 is coupled with a corresponding principal magnetic core constituting a

principal magnetic circuit and carrying an associated magnetic flux ϕM. A control winding 12 is coupled with an associated magnetic core 13 which carries a control flux ϕC. The core 13 having the control winding 12 intersects th principal magnetic core 11 such that the two magnetic fields ϕM and ϕC lie in planes substantially normal to each other. In use of this embodiment, the control winding 12 is either completely de-energised, or is energised to an extent that the core 13 is fully magnetically saturated. When the control winding 12 is not energised, ϕC is equal to zero and a high permeability path is provided around the core 11 for ϕM. When the control winding 12 is energised, ϕC is at saturation value and the magnetic reluctance of the principal core 11 is significantly increased across the gap through which the principal core 11 is intersected by the core 13.

Preferably, the magnetic core 13 carrying the control winding 12 is fabricated from a very high permeability ferromagnetic material, but other materials having lower permeabilities may provide suitable for various specific applications. In the case where a high permeability ferromagnetic material is used, the magnetic reluctance of the principal magnetic circuit constituted by the core 11 across the gap through which it is intersected by the magnetic control circuit constituted by the core 13 when the control winding 12 is energised, is given by the following formula;

$$R = \frac{\ell}{\mu_0 \times A}$$

where R = magnetic reluctance across gap,
ℓ = gap width and therefore thickness of control winding core 13,
$\mu_0 = 4\pi \times 10^{-7}$,
A = cross-sectional area of the principal core 11 at the point of intersection.
Because the principal magnetic circuit and the magnetic control circuit lie in planes which are substantially normal to each other, magnetic coupling between the principal and control windings 10, 12 is practically nil.

An alternative arrangement which also almost excludes magnetic coupling between the magnetic circuits is illustrated in Figure 2. The principal magnetic core 11 is divided into two loops 15, 16 which are both intersected symmetrically by a single core 13 carrying two symmetrical control windings 12a, 12b connected in parallel. Magnetic symmetry is therefore achieved. Hence, any magnetic flux which might be set up by the principal core 11 in the intersecting core 13 carrying the control windings 12a, 12b is self-cancelling and vice-versa, so that cross coupling is, at least theoretically, reduced to zero.

Figure 3 of the drawings illustrates another embodiment of the invention wherein a principal magnetic core 11 carrying a principal winding 10 is provided with a three-stage series intersection by separate cores 13a, 13b, and 13c having different thicknesses and carrying separate respective control windings. Similarly, Figure 4 illustrates a reciprocal arrangement wherein the principal core 11 is provided with a three-stage parallel intersection. In each case, the inductance of the principal winding 10 can be varied in discrete steps by the selective application of separate direct current signals to each of the three separate control windings. Where each of the three intersecting cores 13a, 13b and 13c is fabricated from identical material and th three separate control windings are identical, the steps by which the inductance of the principal winding 10 can be varies are determined by th relative thicknesses of the intersecting cores. For continuous stepped adjustment of the principal winding inductance, maximum resolution is achieved when the three steps of adjustm nt, and therefore the relative thicknesses of th regions of intersection of the cores (whether the control core, the principal core or a combination of both thicknesses), are arranged in binary sequence. Thus, the inductance of the principal winding 10 can be set either by manual switching means or in response to a binary coded signal.

Where the arrangements shown in Figures 3 and 4 of the drawings are applied to th control of power circuits, the arrangement of Figure 3 would normally be connected across a power line as a variable shunt inductor, and the arrangement of Figure 4 would normally be connected in series with a power line as a variable series inductor. Another application of the arrangements shown in Figures 3 and 4 yields a means of digital to analog conversion whereby a binary coded signal is applied appropriately to the control windings to produce a representative analog current determined by corresponding values of inductance exhibited by the principal winding 10. The three stages of intersection shown in each of Figures 3 and 4 are exemplary only and, in practice, a larg number of intersections of the principal core 10 can be arranged to represent a larger number of variation steps or a larger number of bits of binary information.

Figure 5 illustrates a voltage regulating transformer based on th concept of the present invention. A secondary winding is arranged in two stages 20a, 20b to achieve the magnetic symm try described in connection with Figure 2 of the draw-

ings. The central arm 21 of the principal core 11 is intersected in accordance with the aforementioned criteria for th preferred performance of the invention, and one or more direct current signals are applied to one or more corresponding control windings to vary the magnetic reluctance of the principal core 10 selectively, and therefore to vary the magnetic coupling between the primary and secondary windings 10, 20 of the transformer. Appropriate energisation of the one or more control windings can be either in response to external means or to a sensing of the transformer secondary voltage.

Figure 6 of the drawings illustrates a power factor compensation arrangement utilising the invention. A variable inductance 25 shown in the drawing represents a variable inductor in according with the invention, and this can be balanced against a fixed capacitor 26 to compensate against fixed or variable reactive imbalances in power circuits.

The inductive devices described and illustrated herein utilise a novel concept for obtaining selectively variable values of inductance using magnetomotive techniques, while avoiding the need for interworking mechanical parts and substantially reducing or practically eliminating the commonly-encountered problem of harmonic generation and steady state interaction between principal and control circuits.

Claims

1. An inductive device including a principal winding (10), and a principal magnetic circuit (11) having the principal winding operatively coupled therewith so that the reluctance of the principal magnetic circuit influences the inductance of the principal winding, characterised by a control winding (12); and a control magnetic circuit (13) having the control winding operatively coupled therewith whereby the current in the control winding influences the magnetic flux in the control magnetic circuit, the control magnetic circuit being arranged in association with the principal magnetic circuit so that a magnetic flux in the control magnetic circuit at least partially interferes with the principal magnetic circuit, whereby selective control of current in the control winding influences the magnetic flux in the control magnetic circuit which in turn interferes with the principal magnetic circuit so as to thereby influence the reluctance thereof and so vary the inductance of the principal winding.

2. An inductive device as claimed in claim 1, characterised in that the control magnetic circuit (13), is arranged substantially in a single control plane, the control plane being arranged substantially at right angles to at least the region of the principal magnetic circuit (11) subject to the interference by magnetic flux in the control magnetic circuit.

3. An inductive d vice as claimed in claim 2, characterised in that the principal magnetic circuit (11) is arranged substantially in a single principal plane at right angles to the control plane.

4. An inductive device as claimed in any preceding claim, characterised by one or more additional control windings, the or each additional control winding being operatively coupled with a respective one of one or more additional magnetic control circuits (13a, 13b, 13c) arranged relative to the principal magnetic circuit (11) so as to interfere therewith, whereby selective control of the currents in the control winding (12) and in the or each additional control winding enables selective control of the degree of interference with the principal magnetic circuit (11), and hence the reluctance thereof.

5. An inductive device as claimed in any preceding claim, characterised by at least one additional principal winding (20a, 20b) operatively coupled with the principal magnetic circuit (11) so as to enable inductive coupling between said principal winding (10) and the or each additional principal winding, the arrangement being such that the selective control of the current in the control winding (12) enables selective variation of the inductance of, and the coupling between, the principal winding and the or each additional principal winding.

6. An inductive device as claimed in any preceding claim, characterised in that the principal magnetic circuit (11) comprises a principal magnetic core; in that the control magnetic circuit (13) comprises a control magnetic core; and in that the control magnetic core intersects the principal magnetic core so as to enable selective interference with the reluctance of the principal magnetic core by selective control of current in the control winding (12).

7. An inductive device as claimed in claim 6, characterised in that the control winding (12) is arranged to be completely de-energised or to be energised to an extent such that the associated control magnetic core (13) is magnetically saturated.

8. An inductive device as claimed in claim 6 or claim 7, characterised in that the control magnetic core (13) is made of a high permeability ferromagnetic material.

9. An inductive device as claimed in claim 6, claim 7 or claim 8, characterised in that the principal magnetic core (11) is divided into two loops (15, 16) which are intersected symmetrically by a single contr l magnetic core (13), the single contr l

magnetic core having coupled therewith two symmetrical control windings (12a, 12b) connected in parallel, so that any magnetic flux set up by the principal core in the intersecting control core carrying the control windings is self-cancelling and vice-versa, whereby any magnetic cross-coupling between the principal and control magnetic circuits is substantially reduced.

10. An inductive device as claimed in any one of claims 6 to 9, characterised in that the principal magnetic core (11) has a portion thereof defining a series portion of the principal magnetic circuit, said core portion being intersected by a plurality of control magnetic cores (13a, 13b, 13c) each having associated therewith a respective control winding, whereby selective control of the number of control windings energised enables selective control of the reluctance of said series portion of the principal magnetic circuit.

11. An inductive device as claimed in claim 10, characterised in that each of the regions of intersection of the control and principal magnetic cores (13a, 13b, 13c and 11) has a respective different thickness.

12. An inductive device as claimed in any one of claims 6 to 11, characterised in that the principal magnetic core (11) is divided into parallel core portions providing parallel paths for magnetic flux in the principal magnetic core, each parallel core portion being intersected by a respective control magnetic core (13a, 13b, 13c), each control magnetic core having an associated respective control winding, whereby selective control of the current in each control winding enables selective control of the magnetic reluctance in the respective associated parallel core portion of the principal magnetic core.

13. An inductive device as claimed in claim 10, claim 11 or claim 12, characterised in that the dimensions of each respective reluctance control region where each control magnetic core (13a, 13b, 13c) intersects the principal magnetic core (11) enable selective stepping of the principal winding inductance, the individual degrees of influence of the control magnetic cores being in a binary sequence.

14. An inductive device as claimed in claim 13, characterised by switching means responsive to a binary coded signal, the switching means being operative to switch current to respective differing combinations of the control windings in response to the binary coded signal to enable control of the inductance of the principal winding (10) in a stepped fashion.

15. An inductive device as claimed in any preceding claim, characterised by a seconding winding (20a, 20b) operatively associated with the principal magnetic circuit (11) so as to thereby enable magn tic coupling between the principal and secondary windings (10 and 20a, 20b), control of the current in the control winding (12) thereby enabling selective control of the magnetic coupling between the principal and secondary windings.

16. An inductive device as claimed in claim 15, characterised in that the principal magnetic circuit (11) includes a control arm (21) and principal arms symmetrically arranged relative to the control arm, the control arm having associated therewith the control magnetic circuit (13), the principal winding (10) being operatively associated with one of the principal arms, and the secondary winding (20a, 20b) being arranged in two stages in series, each stage being operatively associated with a respective one of the two principal arms.

17. A power factor compensation arrangement characterised by an inductive device as claimed in any one of claims 1 to 15, arranged in parallel with capacitive means (26) to enable compensation against fixed or variable reactive imbalances in an associated power circuit.

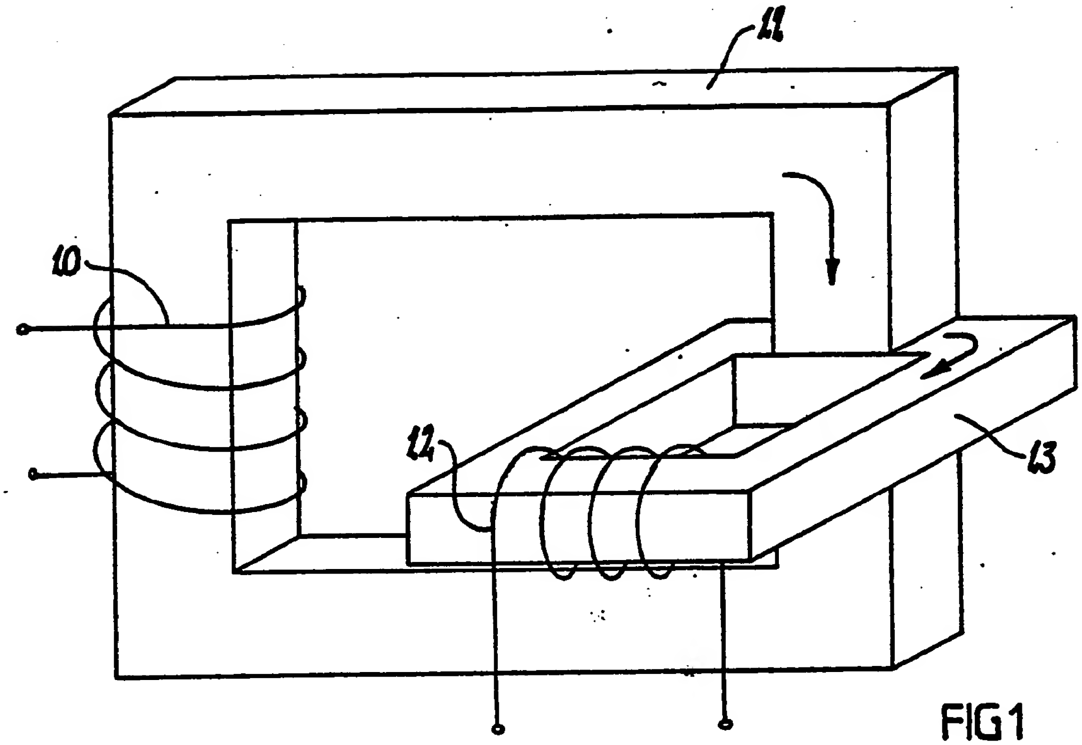

FIG 1

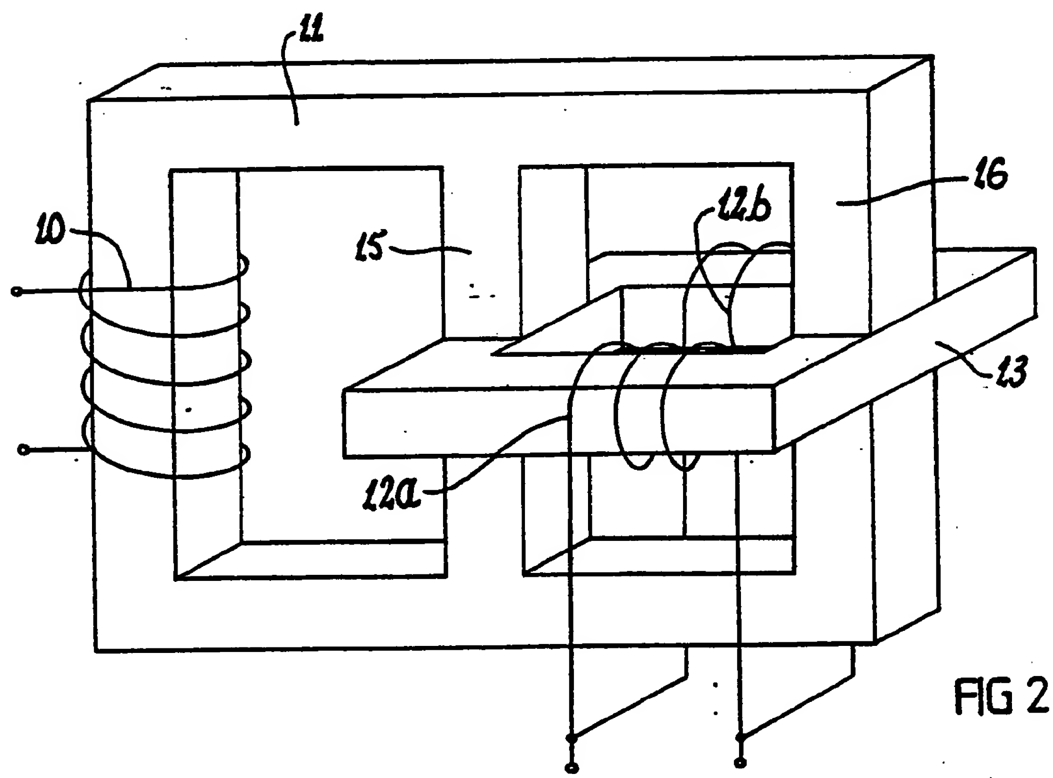

FIG 2

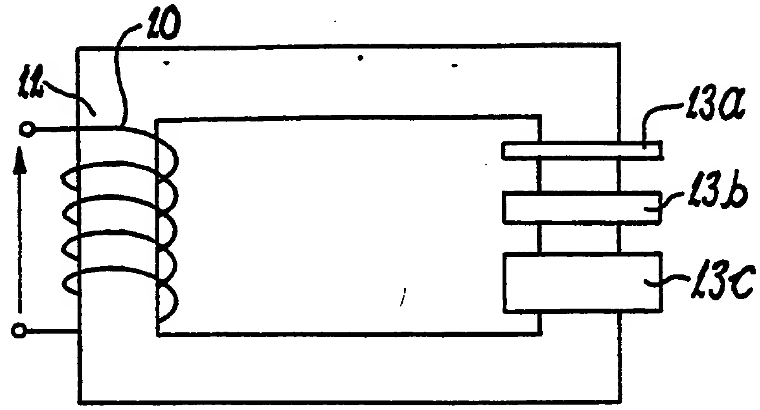

FIG 3

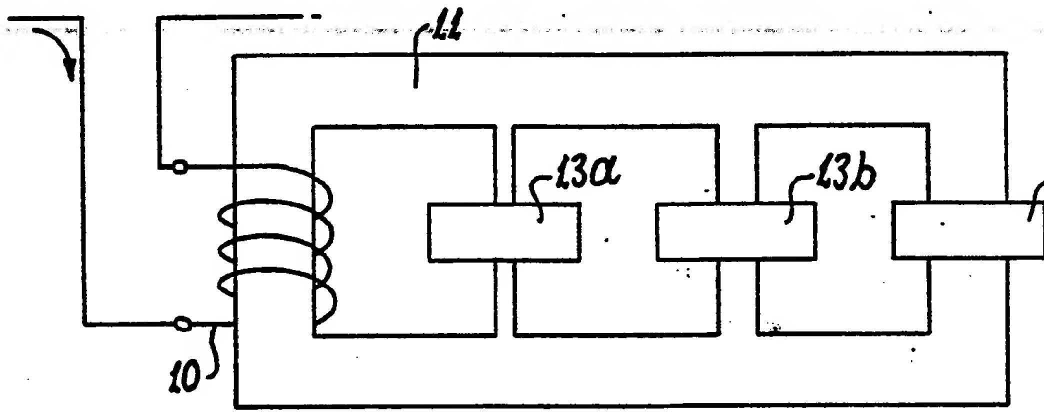

FIG 4

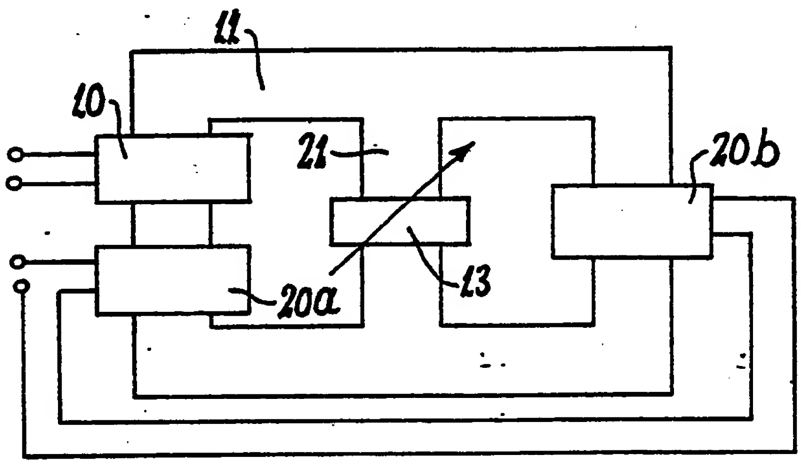

FIG 5

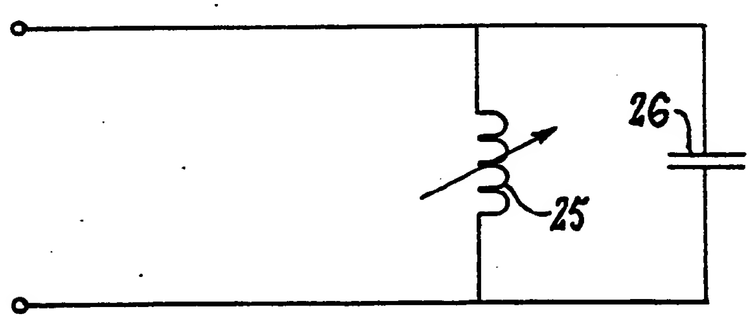

FIG 6

European Patent Office

EUROPEAN SEARCH REPORT

Application number

EP 86 30 3951

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
X	US-A-3 757 201 (L.B. CORNWELL) * Column 2, line 60 - column 5, line 26 *	1-6,10,15	H 01 F 29/14
A		12	

A	GB-A-1 424 986 (RENE VILLASENOR DE RIVAS) * Page 1, line 57 - page 3, line 80 *	1-4,6-8	

E	DERWENT PUBLICATIONS LTD, London, GB; WPIL, AN-86-183106(29) AU-A-85 50 292 (ROYAL MELBOURNE INSTITUTE OF TECHNOLOGIE)		
	---		**TECHNICAL FIELDS SEARCHED (Int. Cl.4)**
A	US-A-3 087 108 (D.S. TOFFOLO)		H 01 F 29/00 H 01 F 21/00

A	PATENTS ABSTRACTS OF JAPAN, vol. 7, no. 65 (E-165)[1210], 18 March 1983; & JP-A-57 211 711 (TOKYO DENKI KAGAKU KOGYO K.K.) 25-12-1982		

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	23-01-1987	VANHULLE R.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if tak n alone
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